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Advanced Optical Daylighting Systems: Light Shelves and Light Pipes

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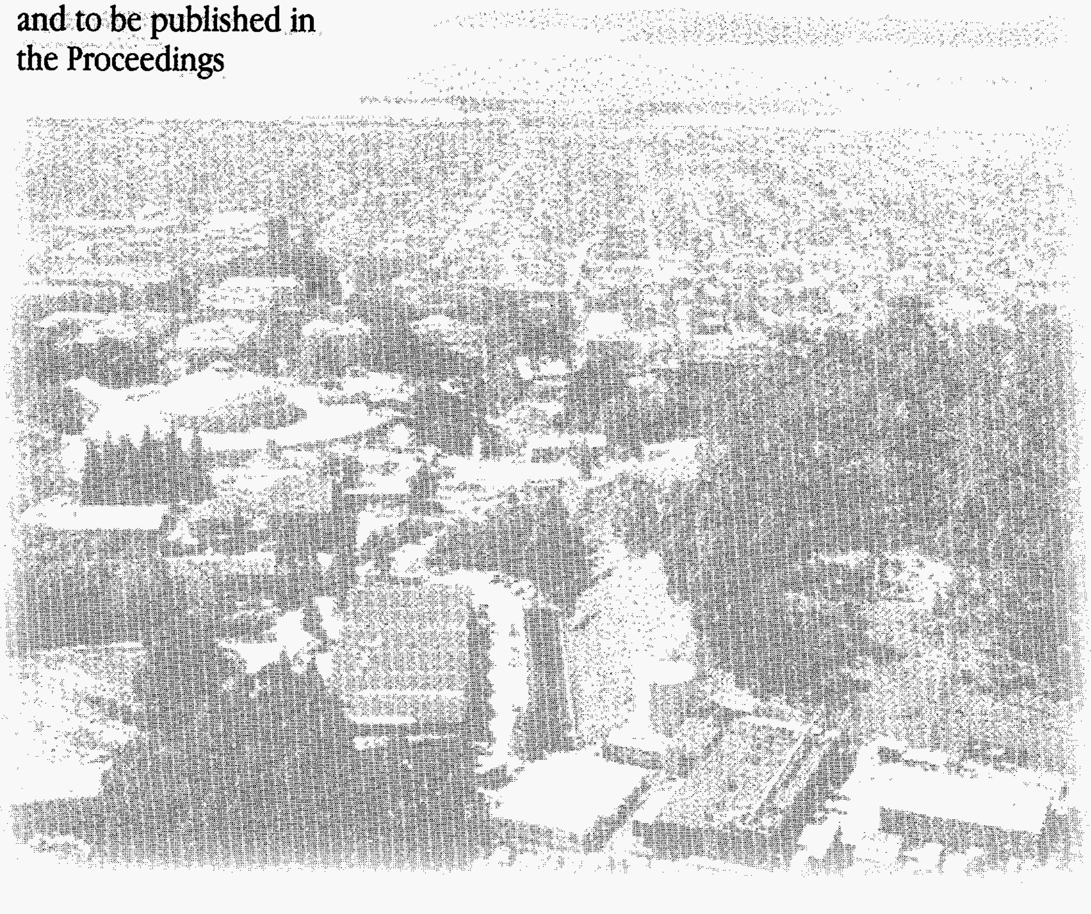

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ABSTRACT

We present two perimeter daylighting systems that passively redirect beam sunlight further from the window wall using special optical films, an optimized geometry, and a small glazing aperture. The objectives of these systems are (1) to increase daylight illuminance levels at 4.6-9.1 m (15-30 ft) from the window aperture with minimum solar heat gains and (2) to improve the uniformity of the daylighting luminance gradient across the room under variable solar conditions throughout the year. The designs were developed through a series of computer-assisted ray-tracing studies, laser visualization techniques, and photometric measurements and observations using physical scale models. Bi-directional illuminance measurements in combination with analytical routines were then used to simulate daylight performance for any solar position, and were incorporated into the DOE-2.1E building energy analysis computer program to evaluate energy savings. Results show increased daylight levels and an improved luminance gradient throughout the year compared to conventional daylighting systems.

INTRODUCTION

Traditional daylight designs can provide adequate daylight within 4.6 m (15 ft) of the window. If daylight can be used to offset lighting energy requirements over a larger floor area, additional energy savings can be obtained. However, the use of larger windows and higher transmittance glazings to provide sufficient levels of daylight at distances further from the window has proven to be ineffective. Daylight levels decrease asymptotically with distance from the window, so that a disproportionate amount of daylight/solar radiation must be introduced into the front of the room to achieve small gains in daylight levels at the back of the room. While this can increase lighting energy savings over a larger floor area, the corresponding increase in cooling due to solar heat gains can offset these savings and exacerbate peak load conditions (Lee et al. 1994). The non-uniform workplane illuminance distribution and luminance gradient within the space can also result in an uncomfortable lighting environment.

In this paper, two advanced daylighting systems—light shelves and light pipes— were designed to provide higher workplane illuminance levels deeper into the space over substantial daytime operating hours during the year. The two systems are presented in detail, along with the methods used for their design, daylighting and energy consumption evaluation. Finally, daylight and energy performance results are presented and discussed, along with recommendations for further research.

BACKGROUND

The objective of most daylighting concepts has been to control incoming direct sunlight, and minimize its potentially negative effect on visual comfort and cooling load. Direct sunlight, however, is an excellent interior illuminant when it is intercepted at the plane of the aperture and efficiently distributed throughout the building without glare. Since direct sunlight contains far more luminous energy per unit area than does diffuse light from clear or overcast skies, it requires a smaller aperture to provide the same quantity of interior illuminance. The planned use of sunlight as an interior illuminant is not a new concept, but there has been few buildings where these concepts have been successfully demonstrated.

The design of light-collecting systems relies upon the reflective and transmissive properties of the surface materials as well as their geometry. Developments in thin-film coatings provide new opportunities for the development of innovative daylighting systems. The two systems proposed here rely on highly reflective films to redirect sunlight more efficiently. This study presents the further development of earlier prototypes (Beltrán et al. 1994) with the addition of side reflectors at the aperture and modified shapes to improve the daylighting performance at more oblique solar angles to the window. A full-scale demonstration of these light-redirecting concepts is docu-mented elsewhere (Lee et al. 1996).

PROTOTYPE DESIGNS

The advanced optical daylighting systems are based on the following concepts:

- By reflecting sunlight to the ceiling plane, daylight can be delivered to the workplane at depths greater than those achieved with conventional windows or skylights, without significant increases in daylight levels near the window. This redirection improves visual comfort by increasing the uniformity of wall and ceiling luminance levels across the depth of the room.
- By using a relatively small inlet glazing area and transporting the daylight efficiently, lighting energy savings can be attained without severe cooling load penalties from solar radiation.
- By carefully designing the system to block direct sun, direct source glare and thermal discomfort can be diminished. The challenge of the design stems from the large variation in solar position and daylight availability throughout the day and year.

The initial design of the prototypes was completed using computer-assisted ray-tracing calculations to determine the geometry of the various light-redirecting optical elements. The designs were tailored to utilize direct sunlight, the intensity of which is four to seven times greater than that of the diffuse skylight (Rosenfeld and Selkowitz 1977). Rays were traced from the target—located at the ceiling, 4.6 to 9.1 m (15 to 30 ft) from the window—back to the reflector, for sun rays incident over the full range of solar altitude angles. Based on the required angles of the incident and reflected solar rays, the optimum angle of the reflector was determined. Hourly sun rays were then traced to verify that no reflected rays were directed downwards, creating direct glare. All prototypes were designed for Los Angeles (34°N latitude).

Efforts were focused on determining the optimum aperture size, reflector size, and reflector shape to take advantage of the optical properties of the daylighting films and to accommodate the particular sun path viewed by the window for a specific orientation and building latitude. The light shelves and light pipes were designed to supplement the daylight provided by a lower vision window and to be the primary source of daylight at 4.6 to 9.1 m (15 to 30 ft) from the window wall. The lower window employs a spectrally selective glazing, accommodates the occupant's desire for view, privacy, etc., and provides daylight up to 4.6 m (15 ft) from the window.

Light Shelves

Four south-facing light shelf designs were developed to fit within a 0.4 to 1.1 m deep (1.5 to 3.75 ft deep) articulated building facade (Figures 1 and 2). The main reflector consists of a curved, segmented surface to better redirect sunlight with changing solar altitudes. Each segment of the surface was carefully calculated, based on the window orientation and site latitude, to ensure that incoming rays would strike the reflector at the optimal angle for redirection into the space. The devices were designed to perform consistently throughout the daily and seasonal range of solar position. The surface of the reflectors uses a compound reflective film which produces two types of reflection: specular and narrow spread. The film is highly reflective (88%), with linear grooves that spread light within an angle of 10 to 12° at normal incidence.

The light shelf designs have a variable reflector depth and one design includes side reflectors to redirect oblique sun angles towards the back of the space. A secondary reflector with a highly reflective specular film (95%) is placed above the main reflector at the ceiling plane near the window to intercept and redirect low winter sun angles (8:00 AM and 5:00 PM) onto the main reflector. The outside aperture of all light shelf designs is relatively small (0.2 to 0.7 m (0.7 to 2.5 ft) in section) and uses a spectrally selective glazing to minimize heat gains. The optical films used in these designs are durable, but performance is compromised when they are scratched or marred. The light shelves, completely sealed from the interior and exterior environment, are protected from dirt and occupant interference.

To maximize the amount of daylight captured by the main reflector while minimizing the distance that the light shelf projects into the room, bi-level (Figure 2c) and multi-level (Figure 2d) reflector systems were developed. These systems increase the glazing aperture at the window plane from 0.6 to 0.9 m (1.9 to 3 ft) and lower the height of the view window from 1.5 to 1.2 m (5 to 4 ft), while reducing the depth of the light shelf from 1.4 to 0.5 m (3.8 to 1.5 ft). In this design, the amount of reflector area employing both specular and compound films has been more than doubled in a slimmer, less intrusive unit (Table 1). Table 2 shows the aperture size of the light shelf designs as a percentage of the floor area of space. To compare the daylight performance of the light shelf designs, a base case light shelf (Figure 2) was defined as a 1.4 m (3.8 ft) horizontal, white matte surface located at a height of 2.4 m (8 ft) above the floor.

Light Pipes

The light pipe was designed to fit within the ceiling plenum, its daylight-receiving aperture flush against the glazed spandrel of the building, so that it could be used with flush as well as articulated facades. This design also has potential as a retrofit in some existing buildings. The light pipe was designed to be used in combination with a lower, vision window. Compared to light shelf, the optical collector of the light pipe can be simpler in design since the enclosed design prevents stray direct sun. Additional design parameters were considered:

- The light pipe needed to be small enough to fit with other building subsystems (mechanical ducts, lighting, structure, etc.) within the ceiling plenum.
- The cross section of the light pipe was varied to study the changes in illumination efficiency and distribution.

- The reflector system needed to partially collimate incoming sunlight to minimize interreflections within the transport section of the light pipe, and to maximize the efficiency of the system.
- The shape of the light pipe transport cross section was altered and various reflector options were investigated to redirect daylight to the workplane.

A total of four south-facing light pipe options were iteratively designed and evaluated (Figures 3 and 4). Light pipe designs with different cross sections were developed. The length was set at 9.1 m (30 ft), the height was constrained to 0.6 m (2 ft), the width of the glazing aperture was varied from 0.6 to 1.8 m (2 to 6 ft), and the cross section width was varied from 0.6 to 1.8 m (2 to 6 ft). A 95% specular reflective film was used on the interior surfaces of the 9.1 m (30 ft) long light transport element to redirect sunlight. The transport element was coupled to reflectors similar to that used in the single-level light shelf with side reflectors. The distribution element at the back end of the light pipe consists of a 4.5 m long (15 ft long) diffuser (with an 88% transmittance) located at the ceiling plane. A diffusing film was used to transmit the daylight; the film has a uniform translucent appearance and is designed to maximize transmittance with minimal back-reflectance. To maximize the overall efficiency of the light pipe and to improve overall daylight distribution within the space, no daylight is transmitted through the light pipe walls for the first 4.6 m (15 ft) from the window.

The first prototype, the base case light pipe (Figure 4a), consisted of a single central reflector at the aperture, with a simple rectangular section in plan view and a trapezoidal section in elevation. The height narrows toward the back end farthest from the aperture. Like the base case, the second prototype Light Pipe A (Figure 4b) also employed one central reflector, but increased the aperture from 0.6 to 1.8 m (2 to 6 ft), thus creating a trapezoidal section in plan view. A constant height and therefore a rectangular section, was maintained in elevation (Table 3). The third prototype, Light Pipe B (Figure 4c), retained the same geometry as the second, but added reflectors on each side of the central reflector. The purpose of the reflectors was to improve collimation of the incoming sun rays and to reduce the number of interior reflections within the transport pipe. In the fourth prototype, Light Pipe C (Figure 4d), the combination of central and side reflectors was retained, and the trapezoidal plan of the previous version was modified so that the rear of the unit was broadened from 0.6 to 0.9 m (2 to 3 ft) in width, while the rectangular section in elevation was changed to the trapezoidal section found in the elevation of the base case light pipe. A further study was conducted using two units of this fourth prototype side by side in the same room. Table 4 shows the aperture size of the light pipe designs as a percentage of the floor area of space.

EVALUATION METHOD

Initially, approximate evaluation methods were used to gain insight into general daylight performance. The design was then refined using more accurate evaluation methods. Reduced-scale models of all prototypes were built to resolve and evaluate critical daylighting, sun penetration, and glare issues. An outdoor test was conducted to evaluate the qualitative daylight performance of each prototype and to observe the daylight distribution and visual characteristics of the space. Finally, experimental measurements under laboratory conditions were used to obtain a more accurate daylighting performance evaluation for all daylight hours throughout the year.

The IDC Method

The simulation of the annual daylight performance of these optically complex systems was accomplished using the Integration of Directional Coefficients (IDC) method, which combines scale-model photometric measurements with analytical computer-based routines to determine daylight factors and daylight illuminance under varying sun, sky, and ground conditions (Papamichael and Beltrán 1993). Using the LBNL Scanning Radiometer, workplane illuminance measurements were taken inside a 1:20 (0.6 in = 1 ft) scale model of an office space with dimensions of 6.1 m (20 ft) in width, 9.1 m (30 ft) in depth, and 3.1 m (10 ft) in ceiling height. The interior surface reflectances were 0.76 for the ceiling, 0.44 for the walls, and 0.21 for the floor. The window wall and ceiling of the scale model were designed to be removable so that alternate designs of the light shelf and light pipes could be mounted and removed easily. The upper daylighting aperture was modeled to isolate the daylight contribution of the two prototype designs, and in combination with a lower window to estimate the total daylight contribution in a typical building configuration. The lower window and all the prototype apertures had a single clear glass of 0.88 visible transmittance.

Workplane illuminance measurements were taken at thirty interior reference points. Five parallel lines of six cosine- and color-corrected Li-Cor photometers were placed in the model to measure the illuminance levels. Photometers were placed at a workplane height of 0.8 m (2.5 ft), at equal distances (0.8 to 8.4 m, or 2.5 to 27.5 ft) from the window wall, and at the centerline, 0.75 m (2.5 ft), and 1.5 m (5 ft) on either side of the centerline (Figure 5). A total of 121 incoming directions of solar radiation at 15° increments, covering the whole hemisphere seen by the window, were used to create a comprehensive set of directional workplane illuminance coefficients for each interior reference point. These coefficients were then used in the SSG (Sun Sky and Ground) computer program, which mathematically integrates the directional workplane illuminance coefficients over the luminance distribution of the sky and the ground, to simulate the daylight performance of the modeled space for 168 sun positions under CIE clear and overcast sky luminance distributions, with a uniform ground reflectance of 0.20.

Multiple SSG computer runs generated a comprehensive set of sun and sky daylight factors for hourly (8:00 AM to 4:00 PM) sun positions of a typical clear day of each of the 12 months for latitude 34°N. These daylight factors were converted into workplane illuminance by multiplying each daylight factor (sun or sky) by the exterior horizontal sun or sky component on a clear sunny day in Los Angeles (Robbins 1986).

Outdoor Physical Model Assessment

The prototype physical scale models, the same used for the IDC analysis, were photographed outdoors under clear sky conditions and representative times of the year. These tests enabled us to obtain an immediate evaluation of the efficiency of the system, to visualize the amount of daylight redirection, to observe how direct sun penetrates the interior space, and to detect the presence of specular reflections or bright areas due to the optical films. Outdoor tests were performed on a clear sunny day, using a heliodon to position the physical scale model.

For the south-facing light shelves and light pipes, photographs were taken for 34°N latitude at 9:00 AM, 12:00 PM, and 3:00 PM on the winter and summer solstices (June 21 and December 21) and on the equinox (March 21 and September 21). Tests were performed for the upper daylighting aperture by itself and in combination with the lower window.

DOE-2 Energy Simulation

Energy performance evaluation of commercial buildings is facilitated by numerical simulation using the DOE-2.1E Building Energy Simulation Program (Winkelmann et al. 1993). The DOE-2 program accepts sophisticated input descriptions of the building and mechanical equipment and calculates zone and/or building level load and energy use data. We performed annual simulations of a prototypical floor in a commercial office building in the inland climate of Los Angeles. The module has four perimeter zones consisting of four offices, each 9.1 m (30 ft) deep by 6.1 m (20 ft) wide, surrounding a central core zone of 595 m^2 (6,400 ft^2) floor area. Floor-to-ceiling height is 3.1 m (10 ft) with a plenum of 0.8 m (2.5 ft) height. The exterior wall resistance was fixed at R11 (U-value=0.51 $W/m^2 \cdot °C$). Continuous strip windows were used in the exterior wall of each perimeter zone with configurations as described above (Figures 2 and 4). A clear, single-pane glazing with a visible transmittance (T_v) of 0.90, a solar heat gain coefficient (SHGC) of 0.86, and an overall U-value of 5.06 $W/m^2 \cdot °C$ (0.9 $Btu/ft^2 \cdot °F$) was used for the base case and prototypes.

We simulated the daylighting performance of each perimeter zone using continuous dimming control with a light output of 0.001% for a minimum power input of 10%. The design illuminance was set at 538 lux (50 fc). The installed lighting power density was set at 16.1 W/m^2 (1.5 W/ft^2). Using the IDC method within DOE-2, daylight levels were calculated at two reference points in each perimeter zone at a height of 0.8 m (2.5 ft) above the floor and at depths of 3.8 m (12.5 ft) and 8.4 m (27.5 ft). Each reference point controlled 50% of the electric lights within the space.

System coil loads were calculated for each perimeter zone. To isolate zone loads from the building/system interactions, a separate single-zone constant-volume system was assigned to each zone. A constant heating system efficiency (0.6) and cooling system coefficient of performance (3.0) converted these loads to energy usage values.

Using the DOE-2.1E building simulation program, we compared lighting energy use of the advanced optical systems to their base case counterparts, where the lower window aperture was not included and the lighting controls were set to dim in the 4.6-9.1 m (15-30 ft) area. This enabled us to isolate the benefits of the daylighting systems alone.

DAYLIGHT PERFORMANCE

Light Shelf Results

Results from the IDC method indicate that for an inlet aperture area of 1.4 m^2 (14.8 ft^2), which represents 2.5% of the floor area (Table 2), the two single-level light shelf prototypes can achieve workplane illuminance levels of over 200 lux (18.6 fc) throughout the year from 10:30 AM to 1:30 PM at a distance of 8.4 m (27.5 ft) from the window wall, under clear sky conditions (Table 5). The single-level light shelf with side reflectors attains 18-70% higher illuminance levels than all the other light shelves at oblique sun azimuth angles at 9:30 AM or 2:30 PM, mostly around the equinox.

The bi-level light shelf can achieve similar illuminance levels to the two single-level light shelves at most times of the year, except during summer midday hours when illuminance levels are 25-48% lower than the single level light shelves. The bi-level light shelf has a glazing aperture area more than twice that of the single-level and 23% more reflector area. All the light shelf designs achieved higher workplane illuminance levels, and so better daylight redirection, than the base case light shelf between 10:00 AM and 2:00 PM, but yielded lower levels in the mornings between 8:00-9:00 AM, and afternoons between 3:00-4:00 PM at a distance of 8.4 m (27.5 ft) throughout the year (Table 5).

Table 6 gives the maximum and minimum daylight levels and the contrast gradient (ratio of maximum to minimum illuminance) across the 4.6-9.1 m (15-30 ft) zone. Figures 6 to 9 illustrate the distribution of light in the space without the lower window. Note that at all times most of the daylight flux from the base case light shelf is distributed to the front area near the window wall. The two single-level light shelves, however, distribute daylight more evenly throughout the space and on all ceiling and wall surfaces. The base case contrast gradient is greater than that of all of the light shelves during mid-day hours throughout the year—about four times that of the single-level with side reflector at noon on the equinox hours (May-July). With the lower window included, the contrast gradient will increase. Under overcast sky conditions, the base case light shelf provides higher illuminance levels throughout the space than all the light shelves primarily due to its larger aperture size and greater sky view (Figure 10). As expected, due to the small window aperture of the light shelf prototypes, the daylight levels under overcast conditions are minimal.

The visual quality of the space with the light shelves is depicted in Figures 11 and 12 for midday of the equinox. Note the high luminance levels at the back of the ceiling and wall surfaces. This luminance uniformity should enhance the perceived value of these systems relative to conventional daylight or electrically lit rooms which have low ceiling and wall luminances. Combined with the daylight contribution of the lower window, the workplane daylight levels within the space provide uniform ambient light throughout much of the year.

Light Pipe Results

The light pipe prototypes performed more consistently throughout the year than the light shelf designs, due primarily to the increased window area, improved geometry and additional reflective interior surfaces. The inlet aperture represents 2.6% of the floor area (Table 4). For the best light pipe (Light Pipe C, Figure 3 and 4d), the workplane illuminance level at a distance of 8.4 m (27.5 ft) from the window wall is over 200 lux (18.6 fc) throughout the year, from 8:30 AM to 3:30 PM (Table 8). The other two light pipes—Light Pipe A (Figure 4b) and Light Pipe B (Figure 4c)—achieve higher daylight levels than the base case light pipe. The workplane illuminance of Light Pipe B is over 200 lux (18.6 fc) throughout the year from 9:30 AM to 2:30 PM, while the same design but with side reflectors is over 200 lux from about 9:00 AM to 3:00 PM. The addition of the side reflectors, the larger distribution area, and the trapezoidal section demonstrate that higher daylight levels (>500 lux (46.5 fc)) can be achieved at the back of the space. The apertures of all the new light pipe designs are 1 to 2.6% of the floor area.

Table 9 and Figures 13-16 illustrate the daylight distribution in the back of the space. Note the increased daylight flux across the 4.6 to 9.1 m (15 to 30 ft) zone with Light Pipe C designs. Light Pipe B distributes daylight more evenly throughout the back of the space and back wall surfaces. The base case light pipe contrast gradient is much greater than that of all of the light pipes for all times throughout the year—about 45 times that of Light Pipe B during equinox morning and afternoon hours (Light Pipe B contrast gradient = 2, base case light pipe = 91). The width of window aperture of Light Pipes A, B and C (1.8 m (6 ft)) are three times larger than the base case light pipe (0.6 m (2 ft)).

Combined with the daylight contribution of the lower window, the light pipes provide adequate and uniform ambient light throughout much of the year. Figures 17 and 18 depict the contribution of Light Pipe C both by itself and in combination with a lower window.

Results show that a single light pipe running along the centerline of the room can deliver adequate illumination to the space. Two light pipes at a distance of 3.0 m (10 ft) will provide more than the required illumination for this 20 by 30 ft floor area. In an open plan, light pipes can be placed every 4.6 to 6.1 m (15 to 20 ft) to evenly illuminate the space.

The back wall plays an important role in the illumination of the space, since light from the pipe that is reflected off the wall can increase workplane illuminance immediately adjacent to it. Figures 17 and 18 illustrate the resultant visual quality of the space with one Light Pipe C for December 21, 12:00 PM. Light pipes have the advantages, over sidelight windows and light shelves, of reducing unwanted glare and direct sun and providing more control than the light shelves over the spatial distribution of light in deep spaces.

ENERGY PERFORMANCE

Using the DOE-2.1E building simulation program, we compared lighting energy use of the advanced optical systems to their base case counterparts, where the lower window aperture was not included and the lighting controls were set to dim in the 4.6-9.1 m (15-30 ft) zone in order to isolate the benefits of the daylighting systems alone. For Los Angeles, the annual lighting energy use of all prototype light shelves was slightly greater (0-3%) than the base case light shelf for a south-facing zone. However, the base case design would not be an acceptable solution since it would admit direct sunlight to the space and create unacceptable sky glare at times. For the same conditions as the light shelves, the annual lighting energy use was 11-18% less than the base case light pipe at the south (Table 11).

The lower daylighting performance of the prototype light shelves can be attributed to the base case's larger unobstructed glazing area, which admits more daylight flux during overcast conditions, and to its admission of direct sun when the sun is low (early morning and late afternoon) and in the plane of the window. Comparison against a deeper base case light shelf (2.1-3.0 m (7-10 ft)) that controls direct sun would have allowed a fairer evaluation (though it may project too much into the room). With the light pipes, the better performance of the prototypes can again be attributed in part to the glazing area; the base case light pipe had significantly less glazing area and may not collimate the light as well for oblique sun angles.

With respect to total electricity use, a representative base case was defined as a 2.13 m (7 ft) high clear glass window with daylighting controls in the 0-4.6 m (0-15 ft) zone only. Other base case types were defined, but this lighting controls design is more representative of typical commercial practice since shading devices, lower transmission glazing, and workstation furniture diminishes daylight availability to the deeper core. All light shelves in combination with a lower clear glass window and daylighting controls in the 0-4.6 m (0-15 ft) and 4.6-9.1 m (15-ft) zones used 10-19% less total annual electricity than the clear glass window base case for a south-facing zone (Table 12). All the light shelf prototypes, except the multi-level, used 8-9% less total annual electricity than the base case light shelf. These savings are related to the small glazing area of the single level and bi-level light shelves. The improved light shelf prototypes with small apertures provide benefits over conventional light shelves with large apertures, reducing cooling loads and glare. For the same conditions as the light shelves, most light pipes achieved 5-9% less annual electricity use than the base case (clear glass window).

The defined base case does not allow one to make a satisfactory and equitable comparison since clear unshaded glazing is rarely used in commercial buildings due to severe direct sun, glare, and heat gains. This modeling approach, however, was limited to the scope of the IDC measurements which did not include other glazing types or the presence of a shading device.

A complete evaluation of the performance of these systems must balance energy and non-energy benefits, since occupant acceptance often determines the success of the system in the real-world. A high transmission clear glass window with unobstructed daylight within the office interior incurs a high cooling and visual comfort penalty, but diminishes lighting energy substantially. With a shading device (e.g., venetian blind), the same window will incur less cooling and visual comfort penalties, but lighting energy consumption increases. With the prototype daylighting systems, cooling and lighting is controlled, and visual comfort is improved through more balanced daylight distribution within the room. Control of direct sun, view, and privacy is achieved in the lower window with manually operated shades, separate from the daylighting aperture.

CONCLUSIONS

These passive light shelf and light pipe designs can introduce adequate ambient daylight for office tasks in a 4.6 to 9.1 m (15 to 30 ft) zone of a deep perimeter space under most sunny conditions with a relatively small inlet area. The light pipe performed more efficiently throughout the year than did the light shelf. The overall aperture area of the best light shelf design was approximately the same as the light pipe aperture 1.1 m^2 (12 ft^2), but the light pipe used more than twice the reflective surface area of the light shelf.

Sunlight is efficiently redirected towards the back of a space not only when the sun is in front of the window but also at oblique sun angles, as the side reflectors redirect the light, achieving workplane illuminance levels consistently above 200 lux (18.6 fc) for the light shelf for about four hours per day and for the light pipe for about seven hours per day throughout the year. Lower but still useful levels of daylight (>100 lux (9.3 fc)) are provided for a greater range of sun angles. A visual inspection of the physical scale model has shown that when the sun is in front of the window, the light shelves redirect virtually all of the sunlight towards the ceiling plane, thus lighting the room depth with a significantly improved uniform luminance gradient. The light pipe provides higher workplane illuminance levels and a bright wall surface in the back of the room, which improve visual comfort. Direct glare from low solar angles has been controlled in all designs by interception and redirection of direct sun towards the ceiling.

The sunlight availability and the sun path seen by the aperture determine the amount of light transmitted into a space with any of these optical systems. The annual luminous performance of these systems is thus highly dependent on sunshine probability at a particular location and the orientation of window apertures. The brightness contrast in the space is also reduced by utilizing illumination from more than one source. In this case, the lower window primarily illuminates the first 4.5 m (15 ft), and the light shelves and light pipes primarily distribute daylight in the 4.5 to 9.1 m (15 to 30 ft) area.

The prototype light shelves and pipes used less total energy over the course of the year than a clear glass, unshaded south-facing window, with significant improvements to environmental quality. Lack of data for a typical base case window condition (e.g., shading, tinted glazing, furniture systems) made it difficult to make an equitable comparison. Notwithstanding these arguments, if both energy and non-energy benefits are considered, we believe that these advanced optical systems solve the problem of inadequate daylight levels at the core of the building without exacerbating the problems of cooling and visual comfort. Further work to develop a good benchmark for comparison is warranted.

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TABLE 1
SUMMARY OF MATERIALS USED IN THE LIGHT SHELF DESIGNS

LIGHT SHELVES	Exterior Glass (ft^2)	Interior Glass (ft^2)	Specular Reflective Film (ft^2)	Compound Reflective Film (ft^2)	White Matte Surface (ft^2)
Base case	37.5	0.0	0.0	0.0	75.0
Single level	14.8	37.5	11.2	87.2	0.0
Single level w/ side reflectors	14.8	37.5	10.0	88.6	0.0
Bi-level	32.0	60.0	36.0	108.0	0.0
Multi-level	50.8	60.0	24.9	196.6	0.0

TABLE 2
GLAZING APERTURE SIZE AS A PERCENTAGE OF FLOOR AREA OF SPACE (600 FT^2) OF THE LIGHT SHELF DESIGNS

LIGHT SHELVES	Aperture Size: % of Floor Area	Aperture height (ft)	Total depth (ft)	Total Reflective Films (ft^2)
Base case	6.3 %	1.9	3.7	0.0
Single level	2.5%	0.7	3.7	98.4
Single level, side refl.	2.5%	0.7	3.7	98.6
Bi-level	5.3%	1.6	2.7	144.0
Multi-level	8.5%	2.5	1.5	221.5

TABLE 3
SUMMARY OF MATERIALS USED IN THE LIGHT PIPE DESIGN OPTIONS

LIGHT PIPES	COLLECTION SECTION			TRANSPORT SECTION		DISTRIBUTION SECTION	
	Cross-section at front	Reflector Area (ft^2)	Glazing Area (ft^2)	Specular Reflective Film (ft^2)	Prismatic Film (ft^2)	Diffusing Film (ft^2)	Cross-section at back
Base case light pipe	2' x 2'	8.4	1.4	2.0	105.0	30.0	2' x 1'
Light Pipe A	6' x 2'	24.1	4.8	315.0	0.0	44.3	2' x 2'
Light Pipe B	6' x 2'	24.8	15.6	315.0	0.0	44.3	2' x 2'
Light Pipe C	6' x 2'	24.8	15.6	308.5	0.0	55.8	2' x 1'

TABLE 4
LIGHT PIPE APERTURE SIZE AS A PERCENTAGE OF FLOOR AREA (600 FT^2)

LIGHT PIPES	Aperture Size % of Floor Area	Total Reflective Films (ft^2)
Base case light pipe	0.2 %	115.4
Light Pipe A	0.9 %	339.1
Light Pipe B	2.6 %	339.8
Light Pipe C	2.6 %	333.3

TABLE 5

WORKPLANE ILLUMINANCE (LUX) OF LIGHT SHELVES AT 8.4 M (27.5 FT)

Illuminance due to sun and sky contribution, modeled with IDC for Los Angeles.

Base case	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
8:00 AM/ 4:00 PM	100	85	77	71	63	67	70	84	86	86	97	107
9:00 AM/ 3:00 PM	158	133	109	97	83	80	90	110	121	137	157	173
10:00 AM/ 2:00 PM	189	154	135	130	111	103	118	143	147	160	190	203
11:00 AM/ 1:00 PM	217	175	157	142	127	118	134	156	171	182	219	225
12:00 PM	237	187	159	143	125	118	132	158	174	195	239	251
Single level	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
8:00 AM/ 4:00 PM	37	37	41	34	19	20	21	37	42	37	35	34
9:00 AM/ 3:00 PM	70	74	87	89	50	35	51	90	86	73	69	72
10:00 AM/ 2:00 PM	123	136	144	159	126	97	125	156	141	132	121	111
11:00 AM/ 1:00 PM	219	255	349	372	275	210	267	353	333	244	216	204
12:00 PM	300	333	506	492	344	262	334	464	479	318	296	285
Single level, side refl.	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
8:00 AM/ 4:00 PM	38	47	64	51	22	23	25	54	65	46	37	35
9:00 AM/ 3:00 PM	85	98	108	100	54	39	56	101	108	95	84	81
10:00 AM/ 2:00 PM	140	182	286	212	123	97	122	205	274	175	138	127
11:00 AM/ 1:00 PM	223	323	370	343	286	220	278	328	354	309	220	190
12:00 PM	324	486	469	451	407	309	394	428	446	462	319	257
Bi-level	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
8:00 AM/ 4:00 PM	69	67	57	48	35	38	39	55	61	66	66	63
9:00 AM/ 3:00 PM	129	127	117	98	63	53	67	103	119	125	127	130
10:00 AM/ 2:00 PM	228	236	216	170	115	97	117	171	214	229	226	213
11:00 AM/ 1:00 PM	393	424	387	320	230	184	227	311	375	407	388	362
12:00 PM	459	540	496	398	264	209	260	384	477	516	453	417
Multi-level	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
8:00 AM/ 4:00 PM	63	67	56	40	27	29	30	45	58	64	61	58
9:00 AM/ 3:00 PM	127	132	107	68	46	39	48	72	108	127	125	124
10:00 AM/ 2:00 PM	223	223	183	125	82	71	84	127	180	214	220	206
11:00 AM/ 1:00 PM	373	419	373	294	189	150	187	283	358	399	367	337
12:00 PM	433	488	417	288	137	113	137	278	399	464	426	398

TABLE 6
MAXIMUM AND MINIMUM WORKPLANE ILLUMINANCE (LUX) AND CONTRAST GRADIENT (CG) ACROSS THE 4.6-9.1 M (15-30 FT) ZONE FOR LIGHT SHELVES WITHOUT LOWER WINDOW

CG=Max./Min. workplane illuminance of 15 sensor measurements.
Note: Values for 3:00 PM are same as the ones for 9:00 AM.

LIGHT SHELVES		Base case			Single level			Single level w/ side refl.			Bi-level			Multi-level		
		max	min	CG	max	min	CG	max	min	CG	max	min	CG	max	min	CG
Dec. 21	9:00 AM	336	45	7	142	0	142	167	18	9	305	25	12	314	34	9
	12:00 PM	490	173	3	323	190	2	314	222	1	586	308	2	641	302	2
Mar. 21	9:00 AM	152	11	14	179	0	179	200	26	8	231	11	21	236	16	15
	12:00 PM	317	71	4	515	277	2	510	345	1	870	341	3	473	329	1
Jun. 21	9:00 AM	45	13	3	26	0	26	26	6	4	32	0	32	19	0	19
	12:00 PM	184	65	3	272	176	2	336	147	2	210	121	2	162	63	3
Sep. 21	9:00 AM	152	11	14	179	0	179	200	26	8	231	11	21	236	16	15
	12:00 PM	324	88	4	490	264	2	487	327	1	828	328	3	458	314	1
Overcast		74	13	6	35	5	7	41	9	5	62	13	5	63	11	6

TABLE 7
AVERAGE WORKPLANE ILLUMINANCE (LUX) AT THE 4.6-9.1 M (15-30 FT) ZONE FOR THE LIGHT SHELF DESIGNS.

Note: Values for 3:00 PM are same as the ones for 9:00 AM.

LIGHT SHELVES		Base case	Single level	Single level w/ side refl.	Bi-level	Multi-level
Dec. 21	9:00 AM	166	55	80	134	145
	12:00 PM	215	244	227	387	421
Mar. 21	9:00 AM	82	65	100	94	104
	12:00 PM	131	364	385	550	366
Jun. 21	9:00 AM	26	12	16	15	10
	12:00 PM	57	193	193	126	65
Sep. 21	9:00 AM	82	65	100	94	104
	12:00 PM	131	364	385	550	366

TABLE 8
WORKPLANE ILLUMINANCE (LUX) OF LIGHT PIPES AT 8.4 M (27.5 FT)

Illuminance due to sun and sky contribution, modeled with IDC for Los Angeles.

Base case	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
8:00 AM/ 4:00 PM	30	34	37	27	12	13	13	28	37	32	28	26
9:00 AM/ 3:00 PM	46	53	54	52	28	21	29	51	53	51	45	44
10:00 AM/2:00 PM	65	72	77	77	57	45	57	75	75	69	64	62
11:00 AM/1:00 PM	128	125	130	126	102	81	100	121	125	119	126	122
12:00 PM	217	218	257	233	164	126	159	220	243	206	213	212
Light Pipe A	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
8:00 AM/ 4:00 PM	40	59	73	57	26	28	30	60	74	57	39	33
9:00 AM/ 3:00 PM	105	130	148	144	90	61	91	144	146	126	103	95
10:00 AM/2:00 PM	261	306	367	432	328	238	320	411	352	292	256	239
11:00 AM/1:00 PM	461	572	682	748	640	482	618	706	647	542	452	411
12:00 PM	490	639	780	816	729	551	704	769	739	606	482	428
Light Pipe B	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
8:00 AM/ 4:00 PM	104	124	143	115	49	52	54	118	142	119	100	86
9:00 AM/ 3:00 PM	227	264	294	304	143	95	145	295	286	253	223	212
10:00 AM/2:00 PM	464	460	448	398	263	201	261	385	432	439	456	437
11:00 AM/1:00 PM	570	595	612	557	434	340	424	534	587	567	560	534
12:00 PM	580	610	641	636	569	440	553	608	614	582	571	553
1-Light Pipe C	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
8:00 AM/ 4:00 PM	136	162	190	147	67	71	74	152	189	155	131	113
9:00 AM/ 3:00 PM	283	311	343	345	179	125	182	338	335	299	278	270
10:00 AM/2:00 PM	589	542	500	524	380	284	375	507	485	518	578	544
11:00 AM/1:00 PM	691	693	723	676	529	419	518	649	695	662	680	673
12:00 PM	759	921	874	820	720	560	700	783	835	876	747	677
2-Light Pipes C	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
8:00 AM/ 4:00 PM	169	204	241	182	78	82	86	187	239	194	162	143
9:00 AM/ 3:00 PM	382	401	429	417	217	149	220	408	418	384	374	367
10:00 AM/2:00 PM	749	731	762	728	484	354	476	698	731	696	735	705
11:00 AM/1:00 PM	798	873	883	775	608	479	595	745	848	832	785	741
12:00 PM	715	848	871	804	649	511	635	773	837	811	705	647

TABLE 9
MAXIMUM AND MINIMUM WORKPLANE ILLUMINANCE (LUX) AND CONTRAST GRADIENT (CG) ACROSS THE 4.6-9.1 M (15-30 FT) ZONE FOR LIGHT PIPES WITHOUT LOWER WINDOW

CG=Max./Min. workplane illuminance of 15 sensors. Note: Values for 3:00 PM are same as 9:00 AM.

LIGHT PIPES		Base case			Light Pipe A			Light Pipe B			1- Light Pipe C			2-Light Pipes C		
		max	min	CG	max	min	CG	max	min	CG	max	min	CG	max	min	CG
Dec. 21	9:00 AM	80	1	80	147	36	4	300	127	2	453	78	6	550	78	7
	12:00 PM	255	65	4	562	177	3	716	272	3	867	265	3	1086	369	3
Mar. 21	9:00 AM	91	1	91	253	78	3	378	165	2	506	102	5	579	102	6
	12:00 PM	272	67	4	905	298	3	736	285	3	874	296	3	1065	322	3
Jun. 21	9:00 AM	31	1	31	75	36	2	113	52	2	158	49	3	173	51	3
	12:00 PM	162	28	6	743	218	3	491	187	3	560	168	3	686	211	3
Sep. 21	9:00 AM	89	1	89	241	77	3	366	161	2	489	103	5	556	103	5
	12:00 PM	259	69	4	855	283	3	702	274	3	835	286	3	1019	311	3

TABLE 10
AVERAGE WORKPLANE ILLUMINANCE (LUX) AT THE 4.6-9.1 M (15-30 FT) ZONE FOR THE LIGHT PIPE DESIGNS

Note: Values for 3:00 PM are same as the ones for 9:00 AM.

LIGHT PIPES		Base case	Light Pipe A	Light Pipe B	1- Light Pipe C	2 - Light Pipes C
Dec. 21	9:00 AM	26	82	175	229	310
	12:00 PM	140	299	393	443	606
Mar. 21	9:00 AM	32	155	217	271	382
	12:00 PM	156	520	429	477	637
Jun. 21	9:00 AM	6	28	37	53	71
	12:00 PM	77	385	265	263	352
Sep. 21	9:00 AM	32	155	217	271	382
	12:00 PM	156	520	429	477	637

TABLE 11
LIGHTING ELECTRICITY USE (KWH) WITHOUT LOWER WINDOW

SOUTH Los Angeles	Case	Dayltg Zones	Ltg Elec. (kWh/ $\text{ft}^2\cdot\text{yr}$)	%Δ Ltg. Elec. Base case Ltsh or Pipe
Base Case	Clear Glass, 7' h	None	4.21	
	Clear Glass, 7' h	0-15'	2.68	
	Clear Glass, 7' h	15-30'	2.89	
Light Shelves	Base case	15-30'	3.77	0%
	Single level	15-30'	3.88	-3%
	Single level, side refl.	15-30'	3.84	-2%
	Bi-level	15-30'	3.75	0%
	Multi-level	15-30'	3.82	-1%
Light Pipes	Base case	15-30'	4.04	0%
	Light Pipe A	15-30'	3.61	11%
	Light Pipe B	15-30'	3.51	13%
	1-Light Pipe C	15-30'	3.39	16%
	2-Light Pipes C	15-30'	3.30	18%

TABLE 12
ANNUAL LIGHTING AND TOTAL ELECTRICITY USE (KWH/FT^2·FLOOR·YR) WITH LOWER WINDOW

SOUTH LOS ANGELES	Dayltg Zones	Total Elec. (kWh/ ft^2·yr)	Lighting Elec. (kWh/ ft^2·yr)	%Δ Total Elec. Clear Glass, 0-15' Dayltg Zone	%Δ Ltg. Elec. Clear Glass, 0-15' Dayltg Zone
Base Case					
Clear Glass, 7' h	None	16.47	4.21		
Clear Glass, 7' h	0-15'	14.47	2.68	0%	0%
Clear Glass, 7' h	0-30'	12.72	1.36	12%	49%
Light Shelves					
Base case	0-30'	13.09	1.79	10%	33%
Single level	0-30'	11.88	1.89	18%	29%
Single level, side refl.	0-30'	11.92	1.92	18%	28%
Bi-level	0-30'	11.72	1.91	19%	29%
Multi-level	0-30'	13.03	2.06	10%	23%
Light Pipes					
Base case	0-30'	13.22	1.70	9%	36%
Light Pipe A	0-30'	13.20	1.53	9%	43%
Light Pipe B	0-30'	13.80	1.50	5%	44%
1-Light Pipe C	0-30'	13.80	1.50	5%	44%
2-Light Pipes C	0-30'	14.66	1.50	-1%	44%

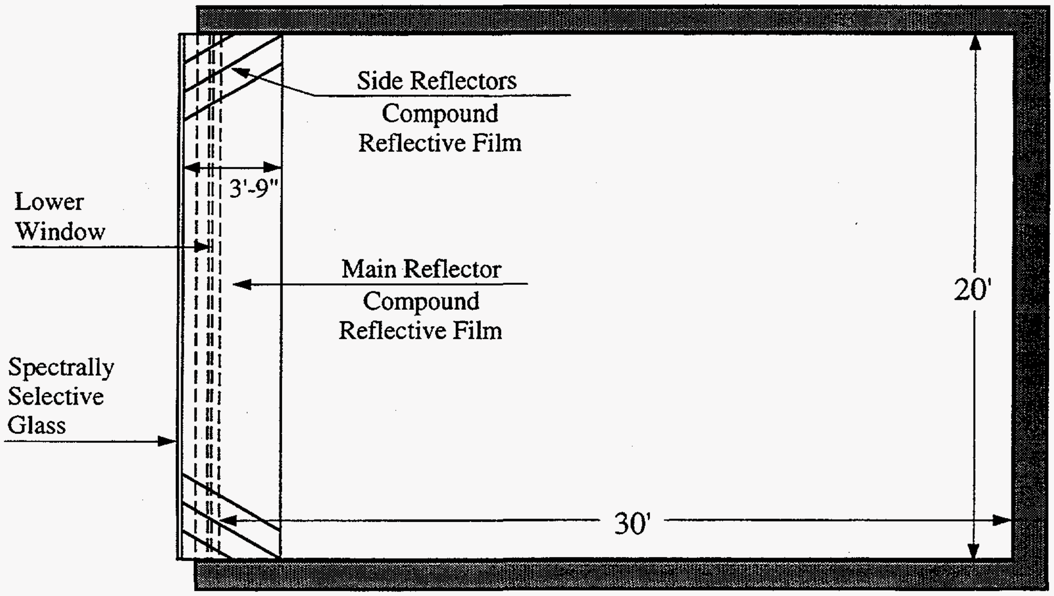


Figure 1. Floor plan of light shelf designs.

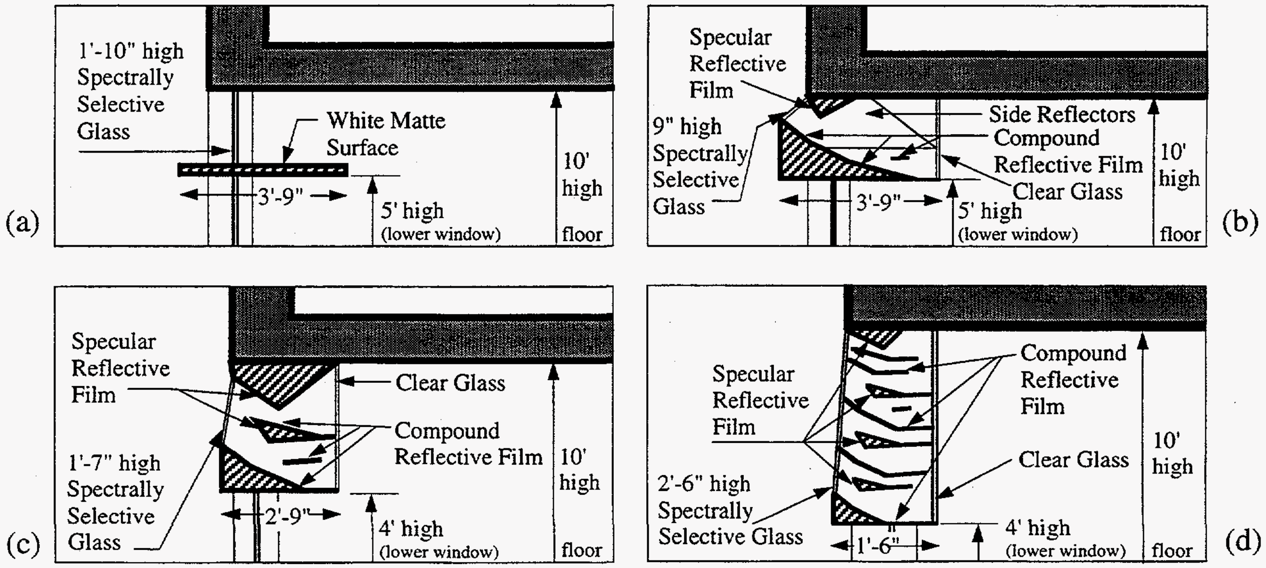


Figure 2. Sections of light shelf designs: (a) base case light shelf, (b) single level light shelf (same section with and without side reflectors), (c) bi-level light shelf, and (d) multi-level light shelf.

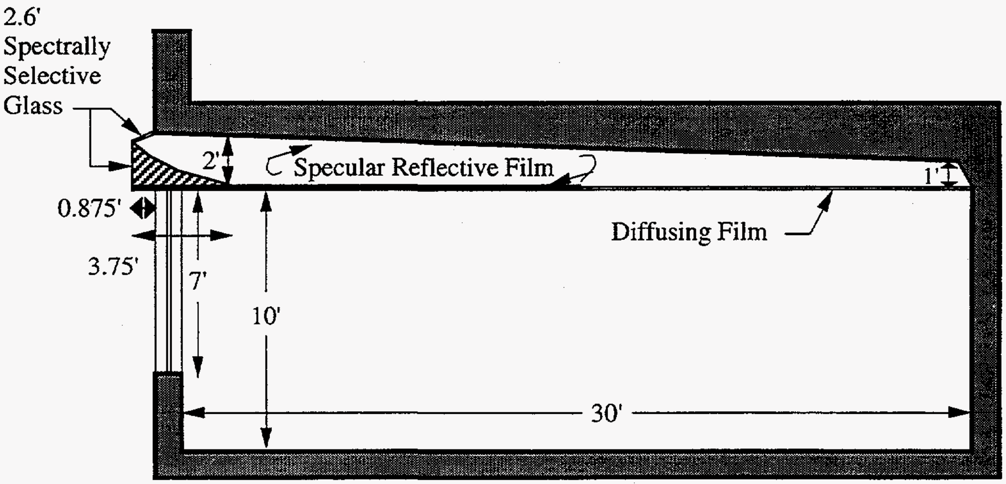


Figure 3. Section of trapezoidal light pipe design (Light Pipe C).

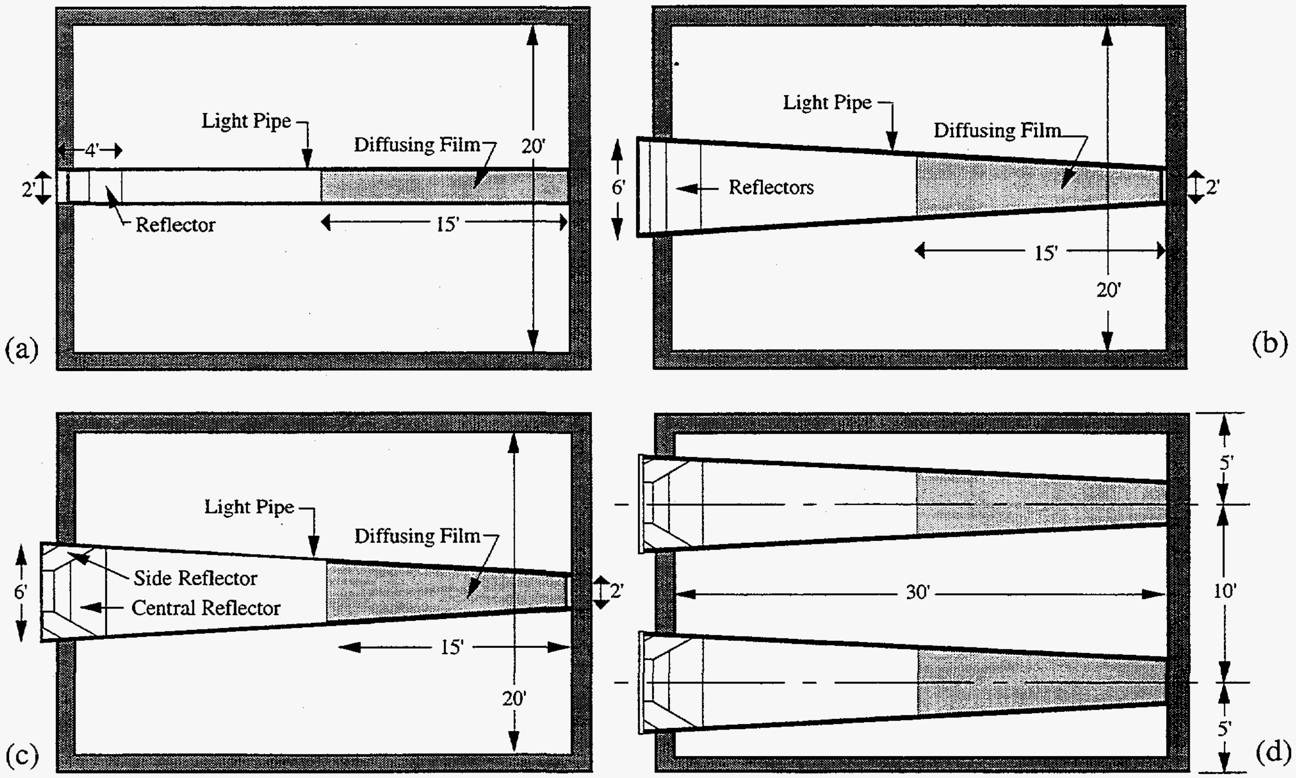


Figure 4. Floor plans of light pipe designs: (a) base case light pipe, (b) Lipe Pipe A: rectangular section light pipe with central reflectors, (c) Light Pipe B: rectangular section light pipe with side reflectors, and (d) Light Pipe C: trapezoidal section light pipe with side reflectors (location of two light pipes in space).

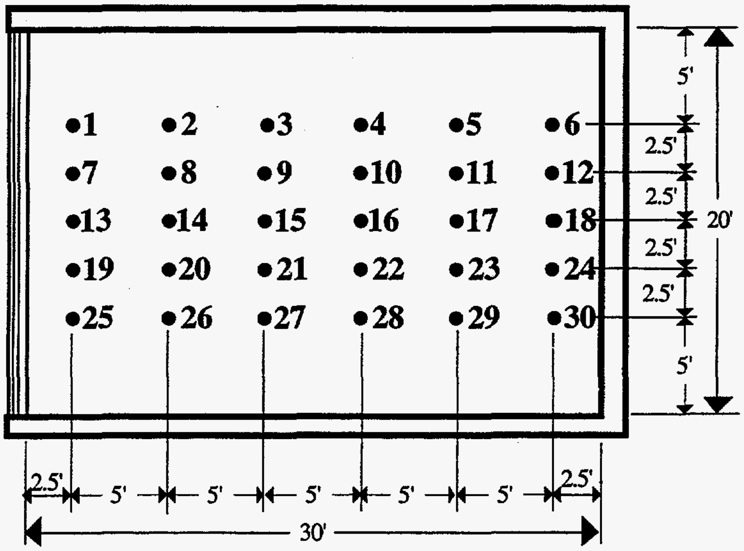
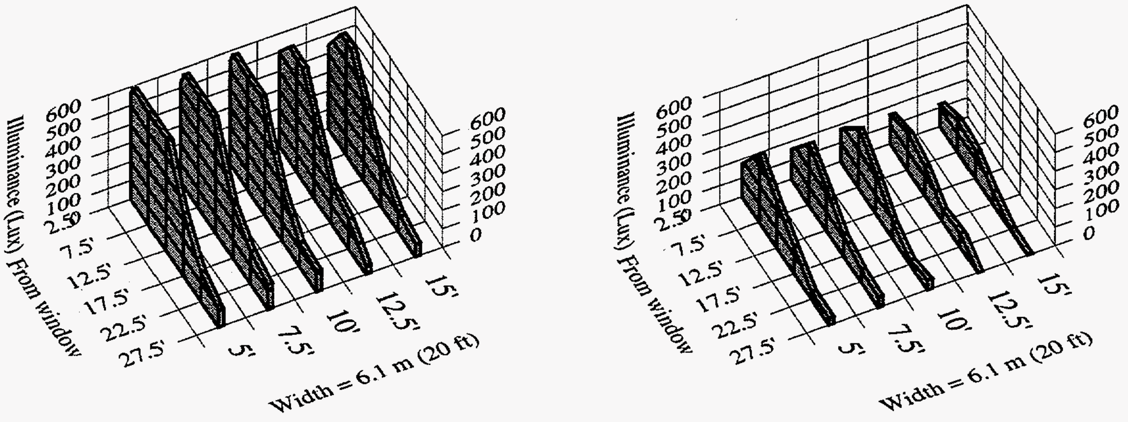


Figure 5. Plan view showing location of sensors in the IDC physical scale model.

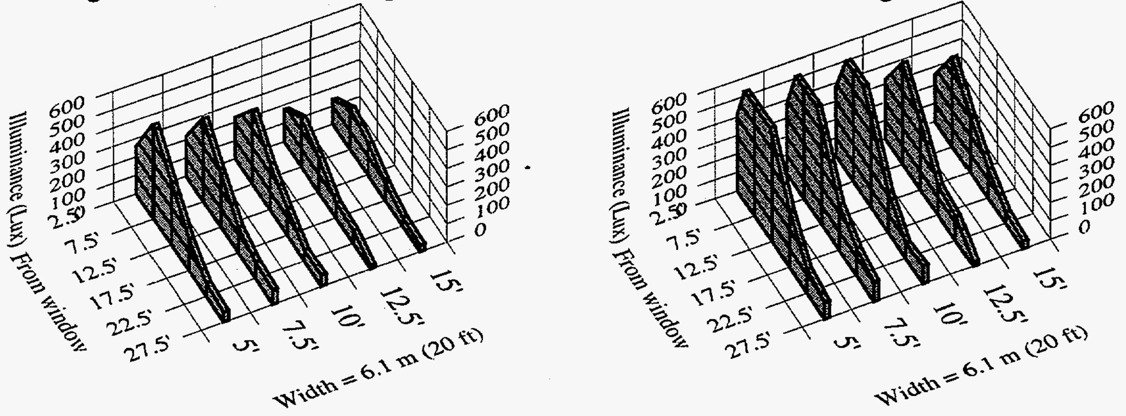
Base case light shelf

Single level light shelf



Single level w/ side refl. light shelf

Bi-level light shelf



Multi-level light shelf

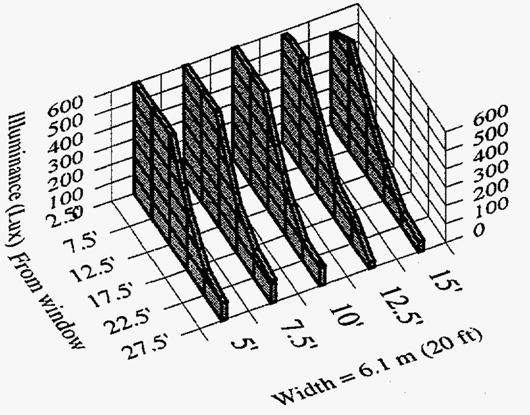
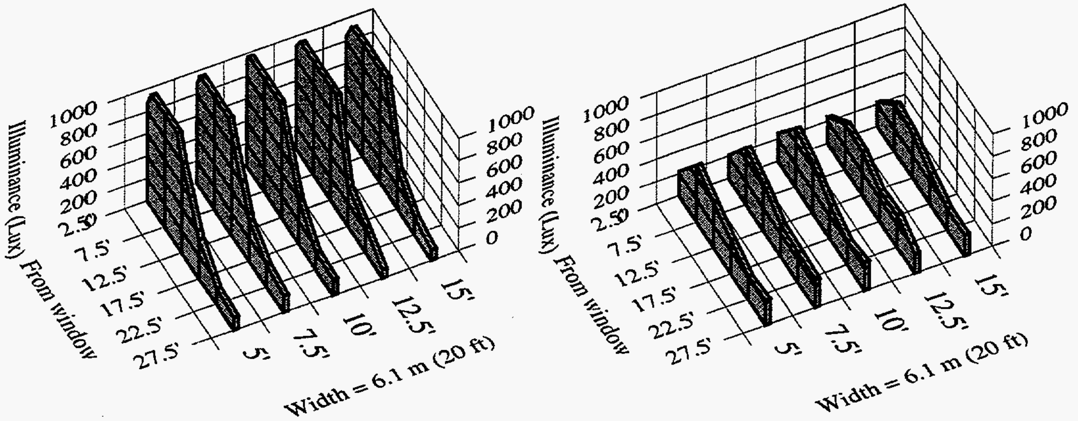
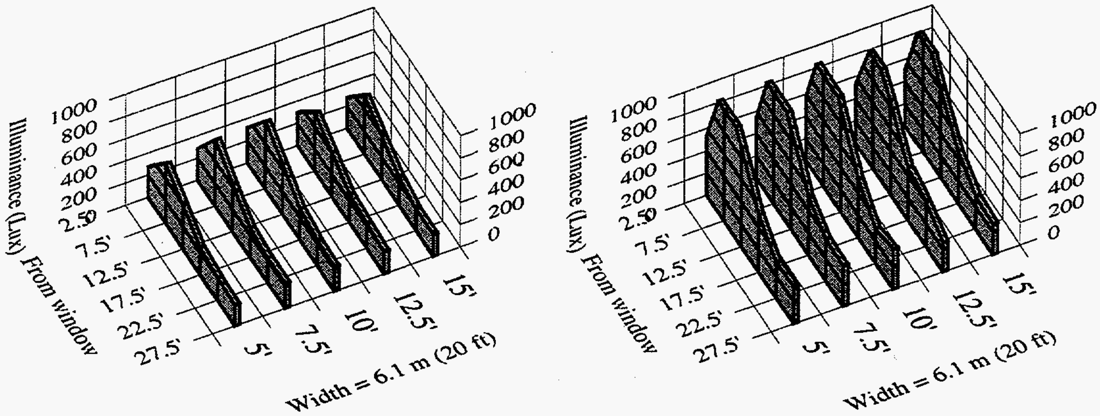


Figure 6. Workplane illuminance (lux) of light shelves modeled with the IDC method for Los Angeles due to sun and sky contribution across the space, on December 21 at 9:00 AM. Exterior horizontal illuminance = 28,590 lux (2656 fc).


Base case light shelf

Single level light shelf


Single level w/ side refl. light shelf

Bi-level light shelf

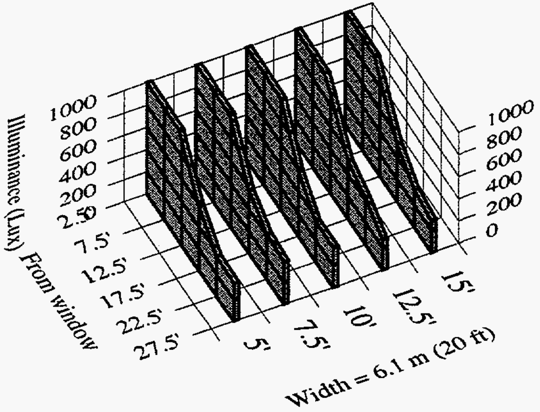
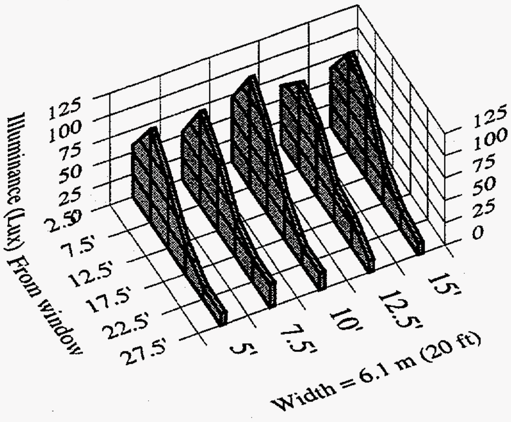
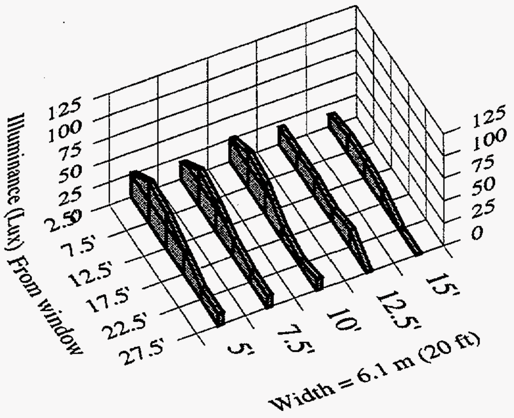

Multi-level light shelf

Figure 7. Workplane illuminance (lux) of light shelves modeled with the IDC method for Los Angeles due to sun and sky contribution across the space, on December 21 at 12:00 PM. Exterior horizontal illuminance = 53,390 lux (4960 fc).

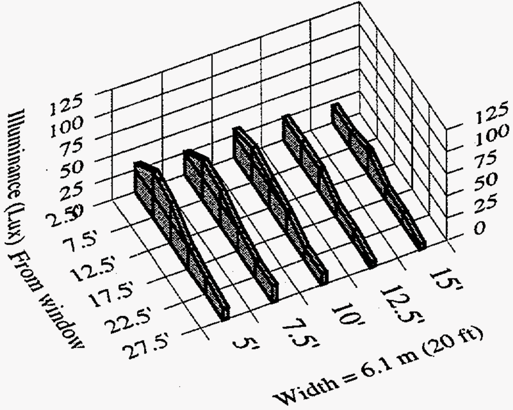
Base case light shelf



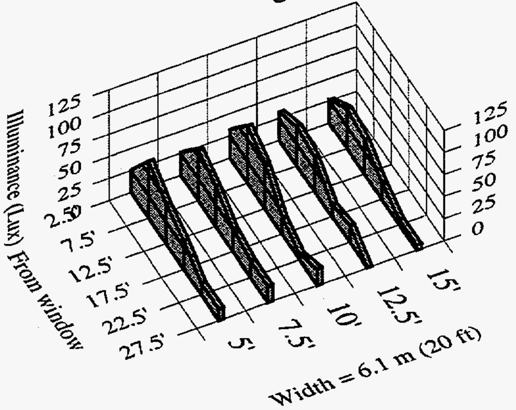
Single level light shelf



Single level w/ side refl. light shelf



Bi-level light shelf



Multi-level light shelf

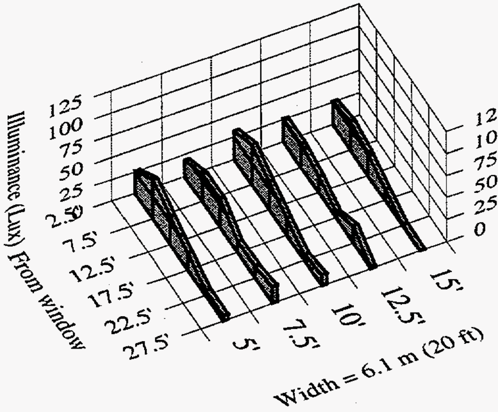


Figure 8. Workplane illuminance (lux) of light shelves modeled with the IDC method for Los Angeles due to sun and sky contribution across the space, on June 21 at 9:00 AM. Exterior horizontal illuminance = 79,350 lux (7371 fc).

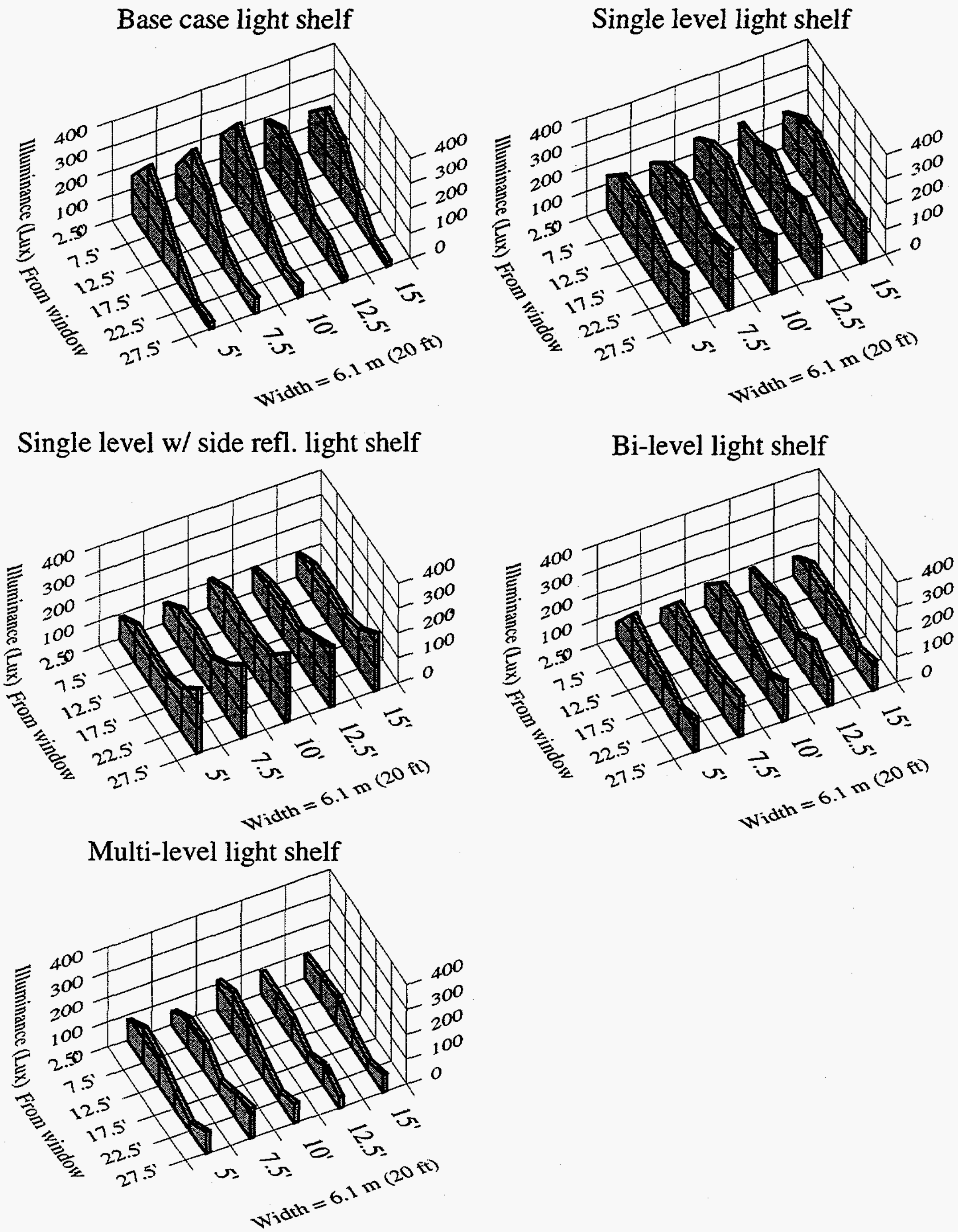


Figure 9. Workplane illuminance (lux) of light shelves modeled with the IDC method for Los Angeles due to sun and sky contribution across the space, on June 21 at 12:00 PM. Exterior horizontal illuminance = 104,500 lux (9708 fc).

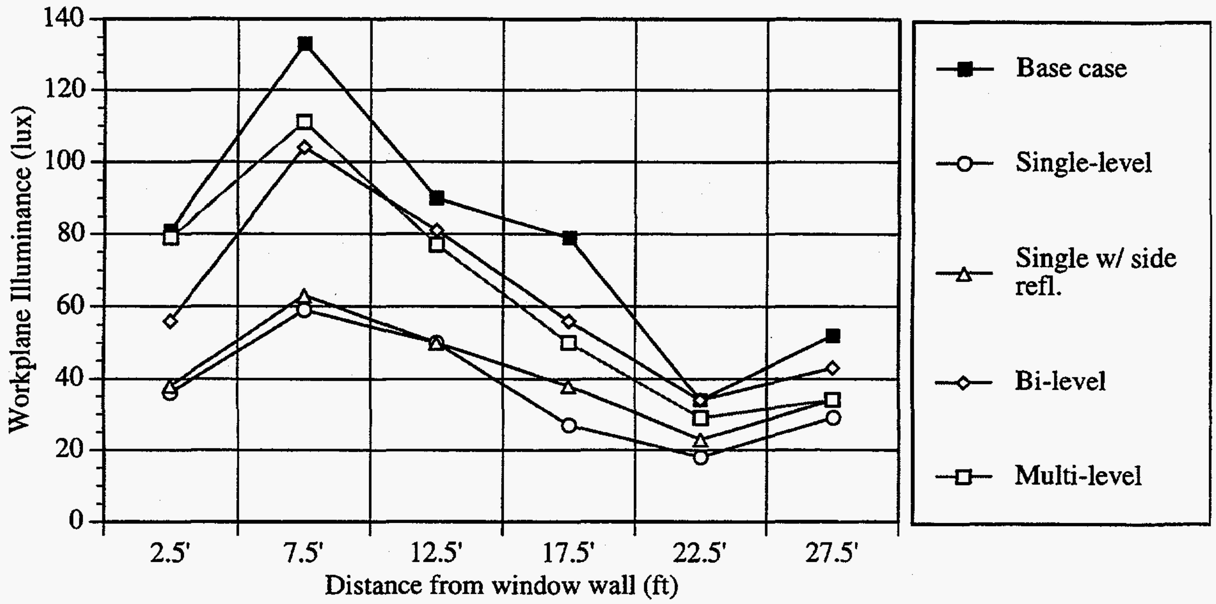


Figure 10. Daylight distribution (lux) of light shelf designs without lower window under overcast sky conditions (Exterior horizontal illuminance = 19,420 lux (1804 fc)).

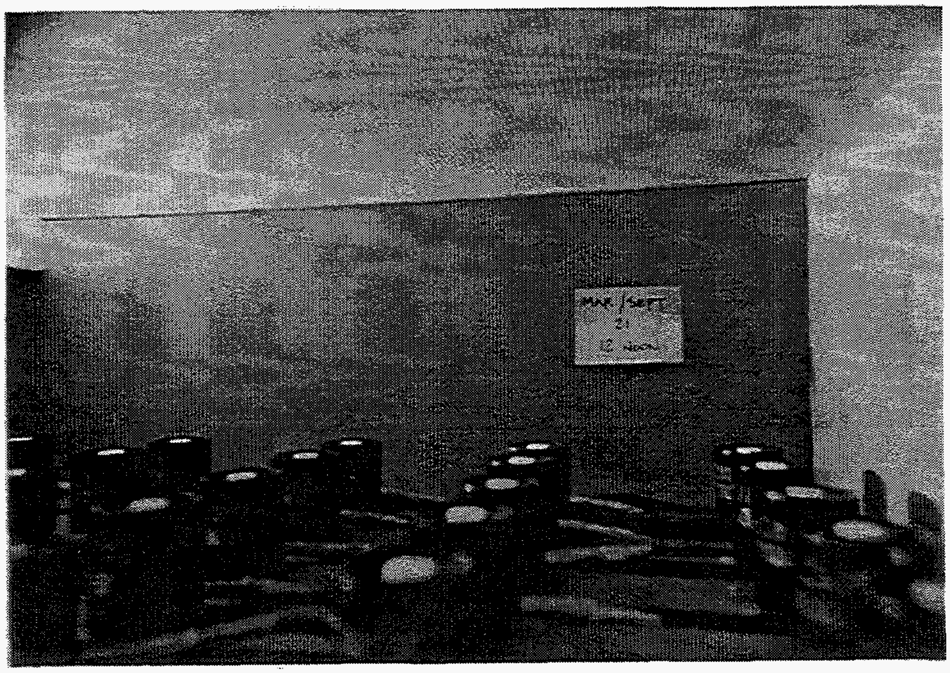


Figure 11. Photograph of single-level light shelf at equinox (March/ September 21) 12:00 PM, 34°N.

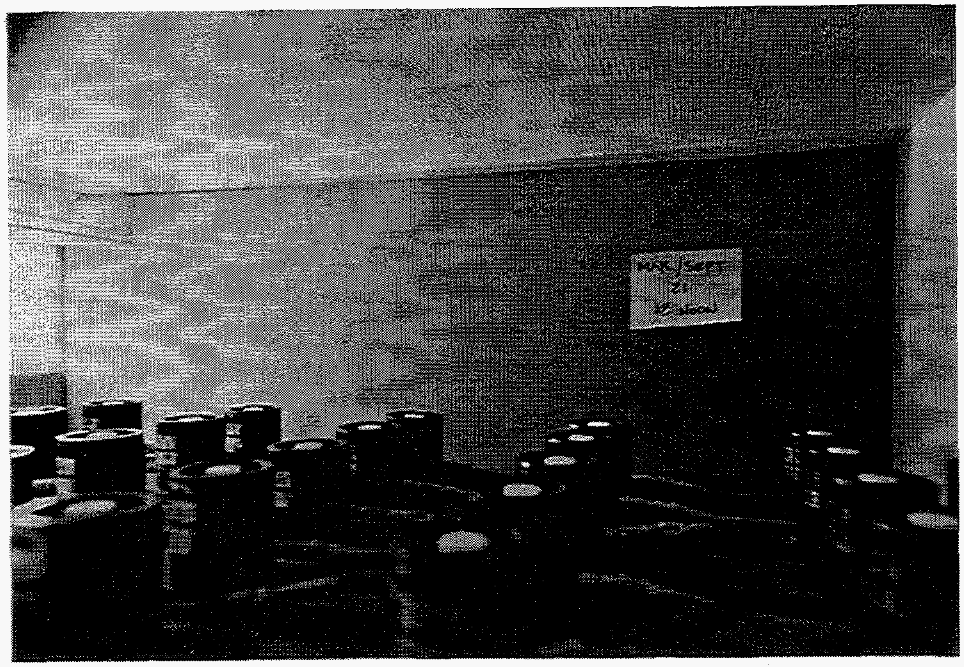
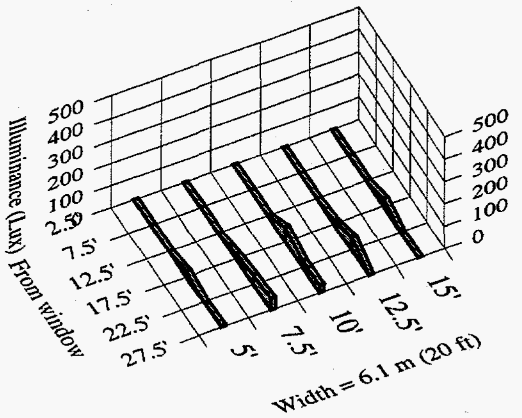
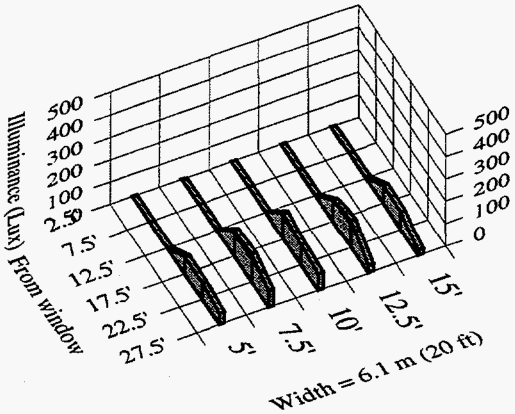


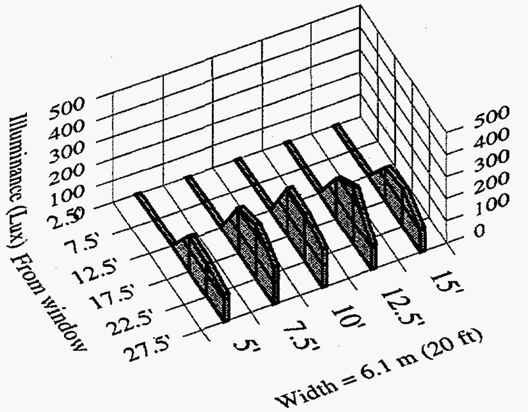
Figure 12. Photograph of single-level light shelf in combination with lower window at equinox (March/Sept. 21) 12:00 PM, 34°N. Note: Although the back wall appears darker than in Figure 11 above, this is an artifact of the automated exposure of the camera which adjusted to compensate for the increased luminance in the front of the room due to the lower window.



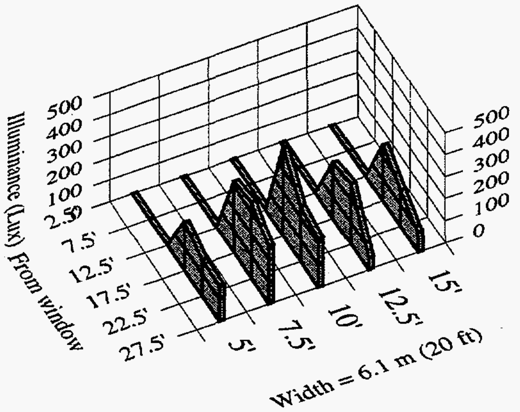
Base case light pipe



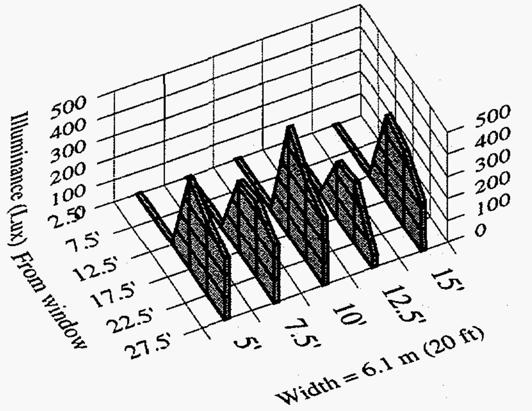
Light Pipe A



Light Pipe B



Light Pipe C (one light pipe)



Light Pipe C (two light pipes)

Figure 13. Workplane illuminance (lux) of light pipes modeled with the IDC method for Los Angeles due to sun and sky contribution across the space, on December 21 at 9:00 AM. Exterior horizontal illuminance = 28,590 lux (2656 fc).

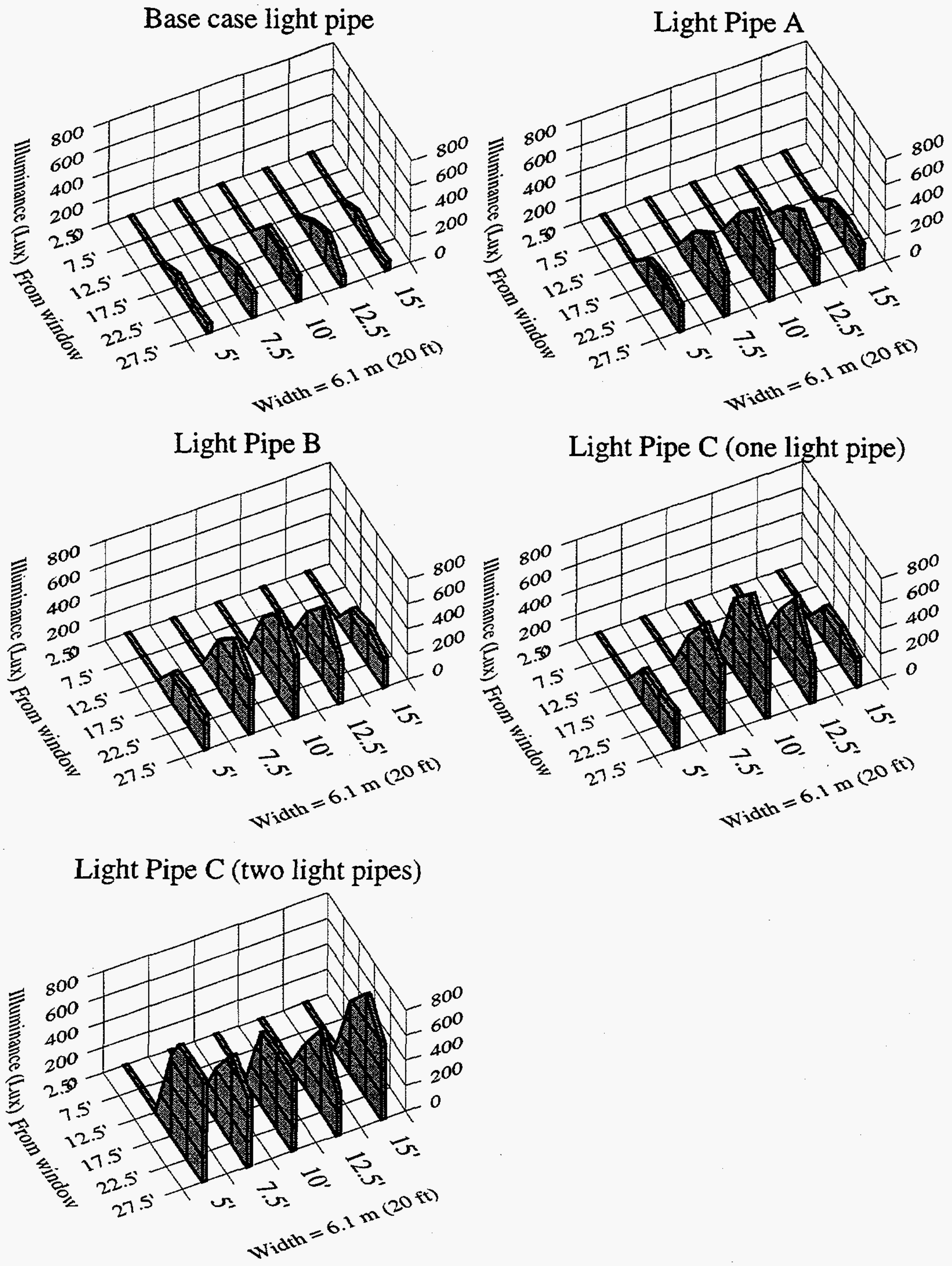
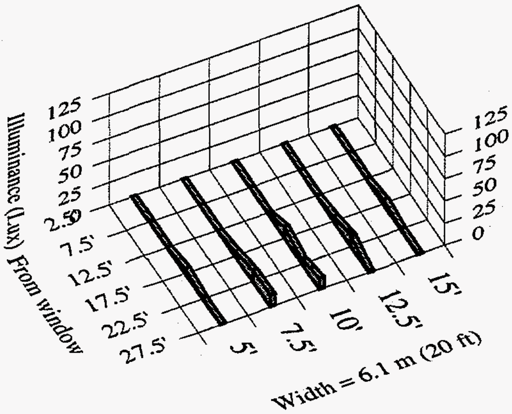
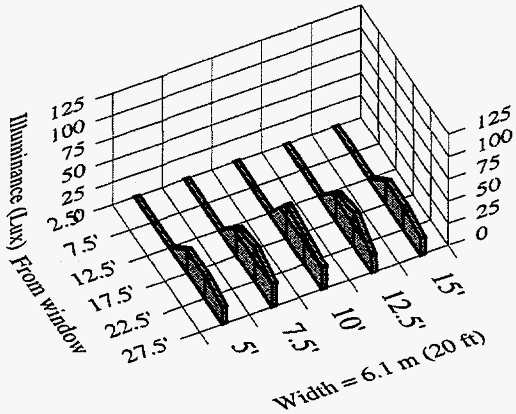


Figure 14. Workplane illuminance (lux) of light pipes modeled with the IDC method for Los Angeles due to sun and sky contribution across the space, on December 21 at 12:00 PM. Exterior horizontal illuminance = 53,390 lux (4960 fc).

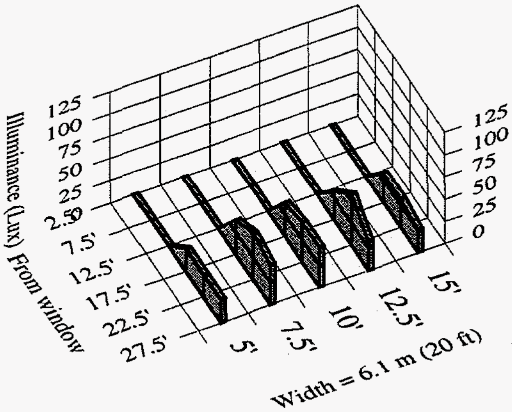
Base case light pipe



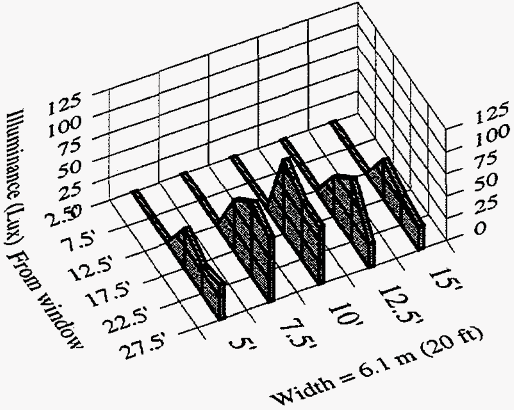
Light Pipe A



Light Pipe B



Light Pipe C (one light pipe)



Light Pipe C (two light pipes)

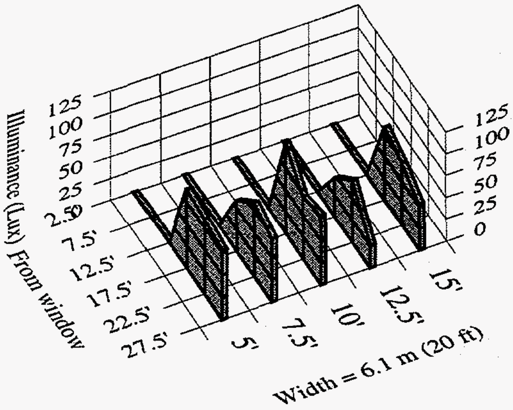
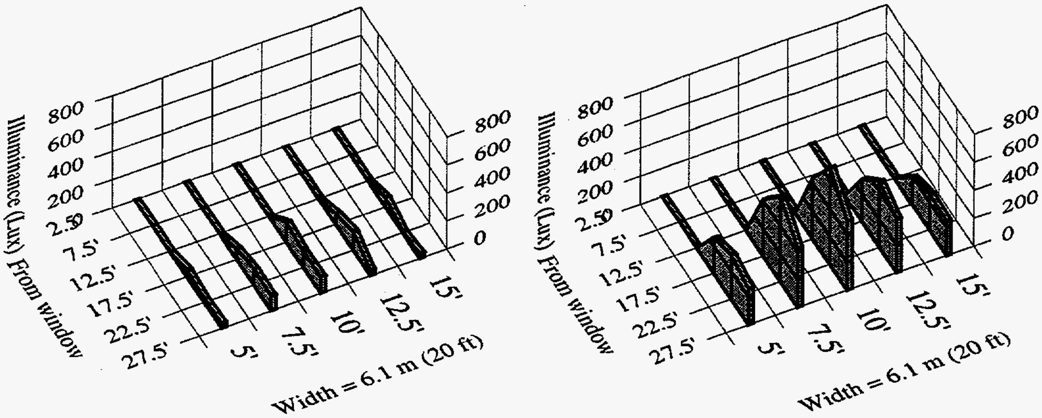


Figure 15. Workplane illuminance (lux) of light pipes modeled with the IDC method for Los Angeles due to sun and sky contribution across the space, on June 21 at 9:00 AM. Exterior horizontal illuminance = 79,350 lux (7371 fc).

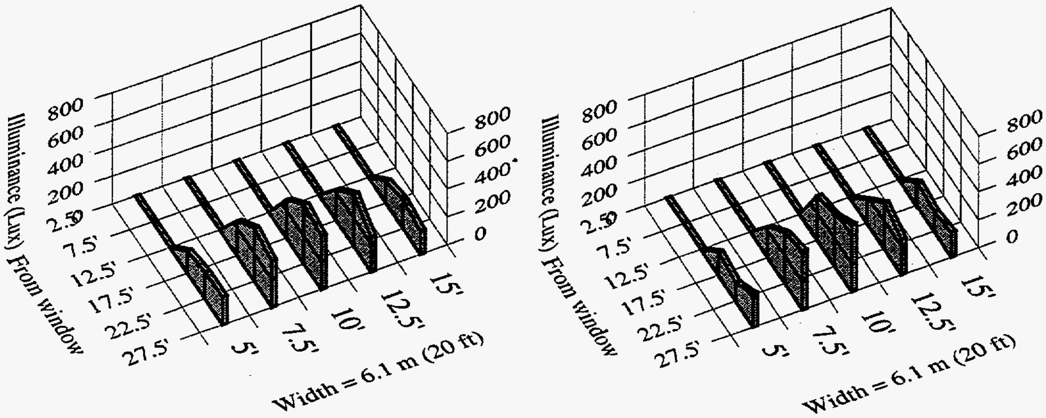
Base case light pipe

Light Pipe A



Light Pipe B

Light Pipe C (one light pipe)



Light Pipe C (two light pipes)

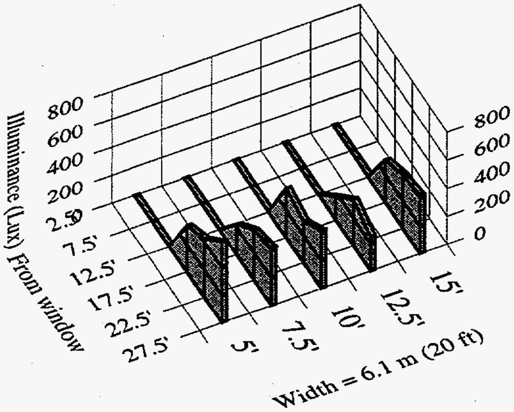


Figure 16. Workplane illuminance (lux) of light pipes modeled with the IDC method for Los Angeles due to sun and sky contribution across the space, on June 21 at 12:00 PM. Exterior horizontal illuminance = 104,500 lux (9708 fc).

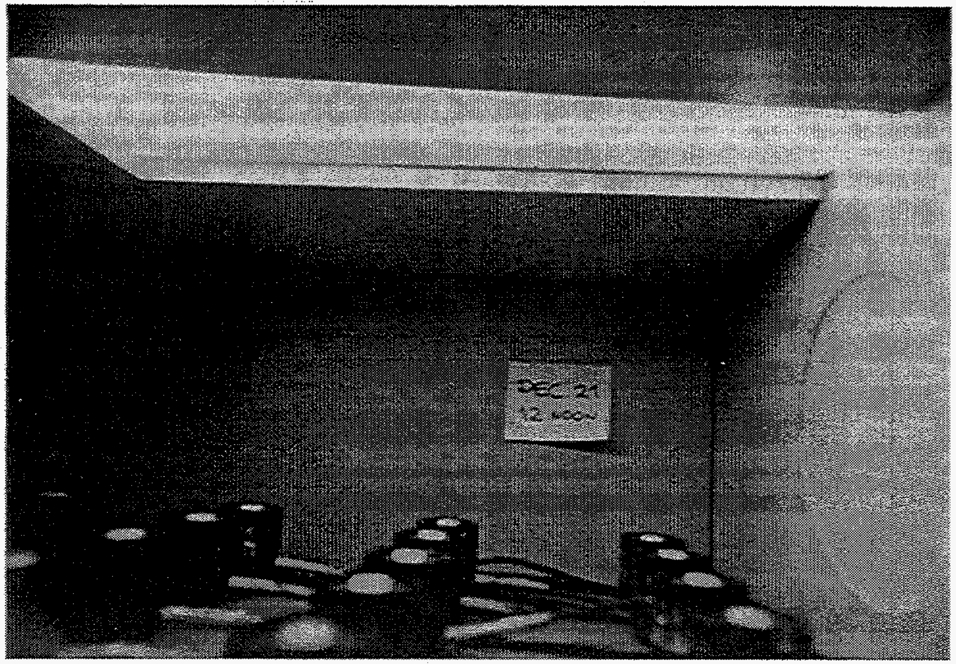


Figure 17. Photograph of one Light Pipe C at December 21, 12:00 PM, 34°N.

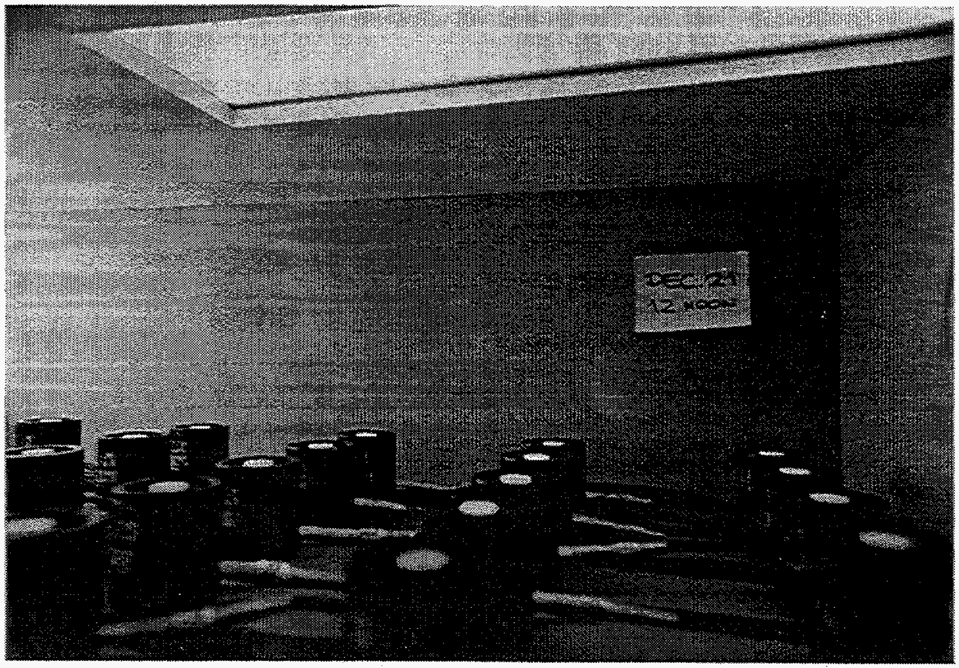


Figure 18. Photograph of one Light Pipe C in contribution with a lower window, at December 21, 12:00 PM, 34°N.